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IONOSPHERIC HEATING ANALYSIS

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13. ABSTRACT

The HF excited plasma line is observed to fluctuate by an order of magnitude about its mean value, the downshifted decay line being about 4/3 the amplitude of the upshifted line. The results obtained by Kantor on the role of the Airy function in explaining one form of the fluctuations has been confirmed.

Red line enhancement and suppression in the airglow have been observed. Suppression of roughly one percent is observed in association with extraordinary mode excitation of the plasma, implying a reduction in the recombination rate, and enhancement of one to ten Rayleighs is observed in association with ordinary mode excitation of the plasma, implying an increase in the impact excitation of the airglow.

The Boulder and Arecibo ionograms during heating experiments exhibit the same general characteristics, although the details vary and are probably related to field line geometry and incident power differences.

In addition to enhancements of the plasma at and near the plasma line frequency and at the ion line frequency, enhancements have been observed at the electron gyro-frequency and at twice this frequency.

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Wave Propagation						
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Plasma Instabilities						
Radio Heating of the Ionosphere						

IONOSPHERIC HEATING ANALYSIS

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FOREWORD

Portions of the work described in this report were performed in collaboration with the staff of the Arecibo Observatory operated by Cornell University at Arecibo, Puerto Rico, and their support is gratefully acknowledged. The following scientists participated in the experiments: R. A. Behnke, M. Biondi, T. Hagfors, J. F. Rose, and V. Wickwar. The report was prepared by the principal investigator, but includes the contributions of the project scientists H. C. Carlson, I. J. Kantor, D. M. Kim, A. R. Laird and R. L. Showen, graduate student Luiz Dias, and assistant F. Schwab.

This technical report has been reviewed and is approved.

Frederick C Wilson

RADC Contract Engineer

IONOSPHERIC HEATING ANALYSIS

SUMMARY

The heating experiments at Arecibo have yielded a number of interesting results derived from the normal absorption of radio waves in the ionosphere (Showen, 1972; Kantor, 1971; Gordon, Showen and Carlson, 1971) and from the anomalous absorption of the high frequency (5-10 MHz) waves and the excitation of plasma instabilities (Carlson, Gordon and Showen, 1972; Kantor, 1972; Dias and Gordon, 1973; Dias, Kim and Gordon, 1973). The results are summarized in previous technical reports and below.

The HF excited plasma line is observed to fluctuate by an order of magnitude about its mean value, the down-shifted decay line being about 4/3 the amplitude of the upshifted line. The results obtained by Kantor on the role of the Airy function in explaining one form of the fluctuations has been confirmed.

Red line enhancement and suppression in the airglow have been observed. Suppression of roughly one percent is observed in association with extraordinary mode excitation of the plasma, implying a reduction in the recombination rate, and enhancement of one to ten Rayleighs is observed in association with ordinary mode excitation of the plasma, implying an increase in the impact excitation of the airglow.

The Boulder and Arecibo ionograms during heating experiments exhibit the same general characteristics, although the details vary and are probably related to field line geometry and incident power differences.

In addition to enhancements of the plasma at and near the plasma line frequency and at the ion line frequency, enhancements have been observed at the electron gyro-frequency and at twice this frequency.

PLASMA LINE ENHANCEMENTS

HF enhanced plasma lines were first observed at the Arecibo Observatory in 1971 (Carlson et al., 1972). A summary of the observations is given by Kantor (1972). Some more recent developments are noted here.

Amplitude Distribution of the Fluctuation of the Decay Line

The amplitude of the decay line is observed, at times, to fluctuate almost one order of magnitude about its mean value (section 6.2, Kantor, 1972). The amplitude distribution of these fluctuations indicates some interesting features. Figures 1 and 2 present the amplitude probability distribution for the downshifted and upshifted decay lines. The solid lines represent the distribution when the transmitted power is 80 kW (the incident power density is approximately 32 $\mu W/m^2$) and dashed lines when the transmitted power is 50 kW ($\sim$ 20 $\mu W/m^2$). Samples of the decay line are taken each 3 seconds, and a histogram of the amplitude is constructed. Note that the amplitude scale is logarithmic.

The following interesting features can be observed:
1) There are big differences between the upshifted and downshifted decay line amplitude distributions. The relation between the upshifted and downshifted amplitudes is not linear (Kantor, 1972). Preliminary results indicate that there is no saturation at the receiver system. A different threshold for the upshifted and downshifted plasma line is an explanation for the result obtained.
2) The upshifted amplitude distribution indicates a saturation at a different level than for the downshifted.

3) The valley in the amplitude distribution of the down-shifted decay line corresponds to an inflection point in the amplitude variation curve with time. The presence of the valley is expected if the amplitude of the inflection point is stable. 4) The difference between the distributions for 50 kW and 80 kW indicate that the amplitude distribution is not proportional to the transmitted power, because the distribution for the two powers cannot be superimposed by a translation.

Further research is being done to investigate the saturation of the decay line, the ion line enhancement, and the relation between them.

Interpretation of Data when the Critical Frequency Falls Through the Heater Frequency

Plasma line data were taken during a time when the critical frequency, f_oF_2, was falling and went through the heater frequency, f_{HF}. Figure 3 shows the amplitude variation with time of the signal-to-noise ratio of the decay line. The interesting point is the amplitude oscillation and it is produced by the sweeping of the height of the parametric instability through the structure of the HF electric field near the reflection height (section 7.6, Kantor, 1972). The data was reanalyzed. The amplitude measurements have now been fully corrected (a weak filter shape effect had been omitted), changed from S/N ratio to equivalent °K, and the electron density scale heights were calculated with a real height ionogram analysis program. Using this more accurate data, the results obtained in section 7.6 of Kantor (1972) are repeated. Ionogram analysis has a real height uncertainty

associated with underlying ionization and valley ionization. This uncertainty was removed by comparison of coincident ionosonde an.)ackscatter data where available for the plasma line range. The altitude where the instability occurs measured with the ionograms is offset by a constant height (5 km) from the one measured using the backscatter radar. This data is being further analyzed to explain the decay of the amplitude.

In Figure 3 the peak SNR for the amplitude of the downshifted decay line is on the average twice the upshifted. The system temperature for the upshifted plasma line is 460°K and for the downshifted 444°K. The antenna gain at the downshifted frequency is 1.45 times higher than at the upshifted frequency. So the peak amplitude of the downshifted decay line, in this case, reduces to 1.33 times the upshifted.

The correlation between the upshifted and the downshifted plasma line tends to be much larger when the f_oF_2 is close to f_{HF}. Fejer (1972) suggested that the variability of the plasma line amplitude is the sweeping through the Airy function structure of the electric field. Kantor (1972) shows that this is the case when f_oF_2 is close to f_{HF}. Since the correlation between upshifted and downshifted intensities decreased when the Airy sweeping was not clearly present, this data suggests the presence of other mechanisms for the amplitude fluctuation.

TEMPERATURE EFFECTS

Several new programs were used in the October heating experiment to improve the measurement of temperatures. One type of experiment uses the Barker decoder to give power profiles with 900 meter altitude resolution. The change in echo power when the heater transmitter is cycled on and off can be related to a change in temperature. Thus measurements of change of temperature with an exceptionally fine altitude resolution have been made and are being analyzed.

Another experiment uses the correlator and an automatic control to turn the heater on and off precisely. This program has measured rise and fall times of electron temperatures with a precision of 1.5 sec. The preliminary analyses show a rise time of about 1 min. and a fall time of about 20 sec.

AIRGLOW OBSERVATIONS

In brief, both red line enhancements and suppressions have been observed. X-mode suppressions of roughly one percent (out of 120 Rayleighs) have been obtained. O-mode enhancements have been observed of about one to ten Rayleighs offering both HF power and enhancement altitude dependence information.

6300 Å airglow enhancements were observed at Arecibo in October due to the HF excitation of the ionospheric plasma. Thus manifestations of the plasma waves produced by the anomalous HF heating is of significance in at least two senses. First, it demonstrates that the Arecibo facility can deliver power densities above the threshold for strongly non-linear plasma density fluctuation enhancements (cases were seen at a factor of four below available transmitted power levels). Second, the data better defines the mechanisms.

The airglow enhancements are attributed to impact excitation by energetic (order of several eV or more) electrons driven by enhanced intensities of fluctuations in the plasma density ("plasma wave temperature"). The airglow enhancements were measured for various powers (power dependence) and over a range of altitudes (altitude dependence of enhancement efficiency). Simultaneous plasma line intensity data (plasma wave temperature) were also gathered providing further information on the energy and altitude dependence of these enhancements. Decay rates of these 6300 Å enhancements should help define molecular nitrogen number densities in the upper atmosphere, a qualitatively new technique afforded by the heating experiment. Decay rates of plasma line enhancements at

this time should better define the damping mechanisms of these plasma density fluctuations, particularly in the strongly enhanced case. Analysis of this data is in progress.

ELECTRON CYCLOTRON LINES

The experiments performed at Arecibo using a 100 kW transmitter tunable between 5 and 12 MHz as a heater to excite artificially the ionosphere (Carlson, et al., 1972) produced many new results, e.g., HF enhanced ion plasma fluctuations and HF enhanced plasma lines. In searching different portions of the spectrum of the 430 MHz backscatter echo, it was found that under certain conditions a new line, typically 2 kHz wide, and with a signal intensity up to 3.5 times the noise, appeared at times near the electron cyclotron frequency and at other times near twice the cyclotron frequency. The lines appeared infrequently, suggesting that stringent ionospheric and experimental conditions must be satisfied.

Experimental Conditions

The experiment was performed at the Arecibo Observatory. The heating transmitter used as an antenna a log-periodic feed mounted near the focus of the 1000-foot dish to produce the ordinary magnetoionic mode of polarization launched vertically and delivered sufficient incident power density into the ionospheric F-region to modify the local plasma. The diagnostics include photometers, ionosondes and the 430 MHz radar. This deals only with the radar results.

A computer controlled data taking program measured the returned power profile, which is recorded on magnetic tape and subsequently the spectrum is computed by means of a fast Fourier transform. A filter of 125 kHz bandwidth can examine the received spectrum with a frequency resolution of 1.12 kHz. The received frequency is controlled by the computer and can be changed every radar interpulse

period. Thus, one is able to look at different portions of the spectrum essentially simultaneously.

Results

Figure 4 shows a typical returned spectrum when the heater is OFF and Figure 5 the same portion of the spectrum when the heater is ON. Note the big enhancement at the plasma line and the appearance of a new line slightly above one or two times the electron cyclotron frequency. The lower hybrid frequency for the prevailing ionospheric conditions was 512 kHz; then the only natural oscillation near these new lines, which are less than 10% of the observed lines, are the gyrofrequency and its second harmonic. It is likely that the spectrum is quasi-symmetrical; the plasma lines have been observed to be nearly symmetrical with respect to the center of the spectrum; however, the weak new lines have not yet been detected in the lower part of the spectrum. The search was extended during the October 1972 heating experiment.

A close look in the vicinity of the line near the electron cyclotron frequency is shown in Figure 6, with the statistical fluctuation denoted by bars from an actual observation.

There is some evidence of a shift of the line frequency with time, suggesting changes in the height of the excited layer and other ionospheric parameters. Further analysis is underway.

The experiments were done in three steps in order to rule out any possible interference: 1) with the heater ON and the receivers connected to the antenna, to record the data; 2) with the heater ON and the receivers connected

to a dummy load, to be sure that the signal was coming from the ionosphere; and 3) with the heater OFF and the receivers connected to the antenna, to be sure that the effect seen was produced by the artificial heating of the ionosphere. The lines were seen only in step 1, which is a decisive proof of their existence. Sometimes the set-up was in step 1 and no lines were observed, either because the filter was looking at a different frequency band or at those frequencies that produced lines, but the ionospheric conditions were such that the oscillations could not be excited.

Observations were made at the following heater frequencies: 5.1, 5.425, 6.79, 8.195, 10.85 MHz, but the best results (higher signal-to-noise) were obtained for f_{HF} = 5.425 MHz and f_{HF} = 10.85 MHz. It is interesting to note that the last frequency is the double of the previous and this is almost 5 times the local electron cyclotron frequency at the height of reflection over Arecibo. A standard computer program computes the electron cyclotron frequency over Arecibo from POGO satellite coefficients (Cain, 1970). The gyrofrequency between 190 and 240 km varies from 1090 to 1070 kHz.

The lines came from a height that is close to the altitude of reflection of the HF signal. At the time of the experiments the reflection was from 190 to 240 km. The change in frequency with time could indicate a reflection from a different height and/or that the frequency of the line is proportional to some time varying parameter; however, at this stage no conclusion can be drawn.

IONOGRAMS, ARECIBO AND BOULDER

Utlaut and Cohen (1971) list effects observed on ionograms due to HF radio wave modification of the ionosphere. The five effects of their tabulation are listed first in Table 1. They are pertinent to ionograms and particularly to the Boulder (geomagnetic 49°N, 316°E) facility described by Utlaut (1970). Table 1 is an expanded version of their tabulation and includes results from ionograms at Arecibo (geomagnetic 30°N, 2°E) ionograms. The symbols are the same as those listed by Utlaut and Cohen except that the symbol "?" has been added. The definitions are as follows:

+	positive results
-	negligible effect
0	results to date not completely conclusive
U	information not yet available
?	not explicitly covered in publications

Effects 6 through 8 are added because of the detailed description of their occurrence at Boulder by Utlaut and Violette (1972), who also observed short-lived sporadic E echoes, possibly connected with HF heating.

Both HF transmitters radiate either O-mode or X-mode waves to the ionosphere, which are deflected from vertical due to the effects of the magnetic field. An ionosonde located at the same site as the transmitter, and sounding vertically at the heating frequency, should obtain echoes from about the same area of the ionosphere the heater is illuminating. This is the case at Arecibo, but at Boulder the heater and ionosonde are separated by about 26 km. Effects seen on the ionograms from the two locations differ

in details because of the different ionosonde and antenna equipment in use, and possibly because of the different magnetic dip-angles, the different characteristics of the HF transmitters, and the distance between the ionosonde and transmitter at Boulder.

The first two effects listed in Table 1, spread O- and spread X-echo, are observed on ionograms at both locations, both day and night, and with O-mode or X-mode HF excitation. There appears to be little difference in the observations made at the two locations for these effects.

In the case of attenuation, however, there may be some real differences between O-mode and X-mode excitations and between Boulder and Arecibo observations. For Arecibo, daytime attenuation of the ordinary mode above the heating frequency is well observed for O excitation; for Boulder, the results are inconclusive. Consistent daytime attenuation of the O-echo due to X-mode excitation has not been seen at either location. At Boulder nighttime O-echo attenuation due to the X-mode excitation is reported to be negligible; at Arecibo it is more pronounced. The observations of X-echo attenuation are more consistent (i.e., inconclusive or negligible) for both locations, the exception being that X-echo attenuation at night with X-mode excitation appears to be more pronounced at Arecibo than at Boulder. Mathews (personal communication) has suggested that at Arecibo a significant amount of X-mode (or O-mode) may be transmitted for nominal O-mode (X-mode) transmission, a factor which should be investigated before any physical significance can be attached to the differences in attenuation seen at the two locations.

It is not clear from published material whether branched O-echoes or X-echoes near penetrating frequencies have been observed at Boulder for daytime O-mode or X-mode excitation, but at Arecibo there is an observation of both effects with X-mode excitation and an observation of a split trace near the O critical frequency with O-mode excitation. The effect is observed at both locations at night for both modes of excitation.

The frequency gap in, or attenuation of, the first multiple reported by Utlaut and Violette is also observed at Arecibo, where the greater virtual height range of the ionograms (0-1000 km) allows the second multiple return which often shows complementary effects (Figure 7). Daytime observations are reduced at either location due to D region absorption, but the smaller virtual height range (0-700 km) for Boulder ionograms may also hinder attempts to observe daytime first multiples.

Possible E region effects of HF heating include a short-lived enhancement of the top frequency of Es layers seen at both locations, attenuation of E-region echoes, and on one occasion at Arecibo what appeared to be production of "range type spread" in an intense natural sporadic E layer.

The agreement between observations at Boulder and Arecibo indicates that there is little qualitative difference in the response of the ionosphere to HF heating. Quantitative verification of this will require a rigorous examination of equipmental effects, of the geomagnetic factor, differences in percentage occurrence of natural spread F at the two locations.

It seems clear from this comparison that future interpretation of ionogram effects due to HF heating should aim toward establishing a unified description of ionospheric response in terms of plasma frequency, height, deflection of the HF radio waves, deflection of the ionosonde radio waves, power flux at the height of absorption, and time.

HF IONOSPHERE MODIFICATION AT BOULDER AND ARECIBO

		O-excitation				X-excitation			
		Day		Night		Day		Night	
	Effects on Ionograms	B	A	B	A	B	A	B	A
1	Spread O echo	+	+	+	+	+	+	+	+
2	Spread X echo	+	+	+	+	+	+	+	+
3	Attenuation of O echo	0	+	+	+	0	0	–	+
4	Attenuation of X echo	0	0	–	–	0	0	–	+
5	Delayed broadband echo	0	0	+	+	0	0	+	0
6	Branched penetrating frequency - O	?	+	+	+	?	+	+	+
7	Branched penetrating frequency - X	?	U	+	+	?	+	+	+
8	Frequency gap or attenuation of 1st or 2nd multiple	?	+	+	+	?	+	+	+
9	Possible E region effects	+	+	+	+	?	U	?	U

After Utlaut and Cohen, 1971. Summary of experimental observations.

B - Boulder
A - Arecibo

\+ - positive results
— - negligible effect

0 - results to date not completely conclusive
U - information not yet available
? - not explicitly covered in publications

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FIGURE CAPTIONS

Figure 1 Amplitude probability distribution for the downshifted decay line. The relative probability scale is linear and starts at zero. Note the peak SNR is logarithmic. The probability distribution is given for two transmitted powers.

Figure 2 Same as Figure 1 for the upshifted decay line.

Figure 3 Peak SNR of upshifted and downshifted decay line variation with time.

Figure 4 Typical returned backscattered echo, when the HF transmitter is not in operation, for a given height.

Figure 5 Same portion of the spectrum of the returned echo, for the same conditions as in Figure 4, but with the HF transmitter in operation. Note that the new lines are slightly above $(430 + f_g)$MHz and $(430 + 2 f_g)$MHz.

Figure 6 Detailed view of the oscillation developed near the electron gyrofrequency, for a specific run, on March 15, 1972. This line is 8.30% above the gyrofrequency computed from POGO satellite coefficients. The frequency position of this line is seen to change with time, but remains above the computed gyrofrequency. The height of reflection was at approximately 250 km.

Figure 7 Ionogram showing attenuation of the first multiple at high frequencies. The second multiple shows greater attenuation than the first multiple at lower frequencies (a normal effect), but less attenuation at higher frequencies than the first multiple.

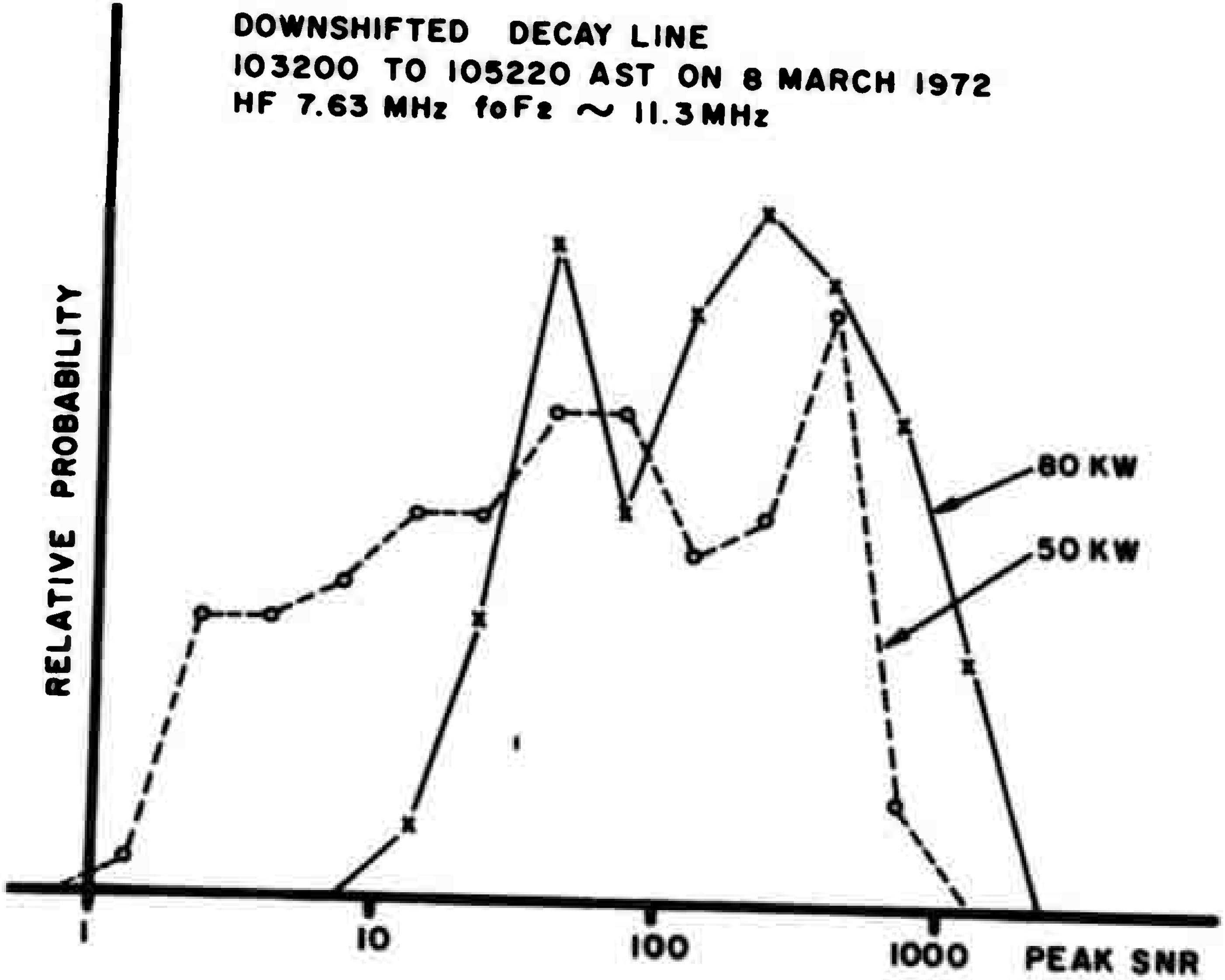

DOWNSHIFTED DECAY LINE
103200 TO 105220 AST ON 8 MARCH 1972
HF 7.63 MHz foF2 ~ 11.3 MHz
RELATIVE PROBABILITY
80 KW
50 KW
1
10
100
1000
PEAK SNR

FIGURE 1

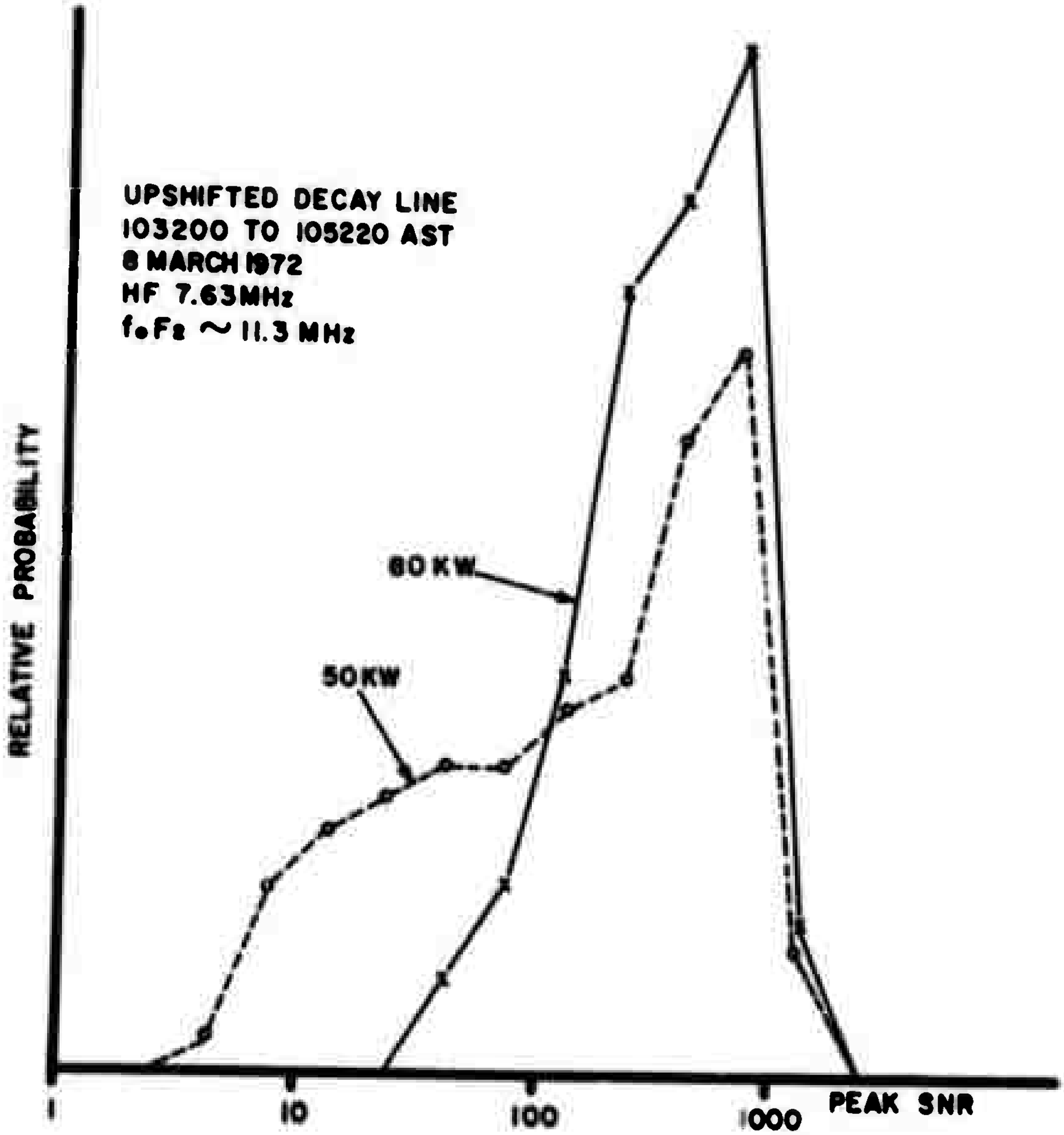

UPSHIFTED DECAY LINE
103200 TO 105220 AST
8 MARCH 1972
HF 7.63MHz
$f_oF_2 \sim 11.3$ MHz
RELATIVE PROBABILITY
60 KW
50 KW
1
10
100
1000
PEAK SNR

FIGURE 2

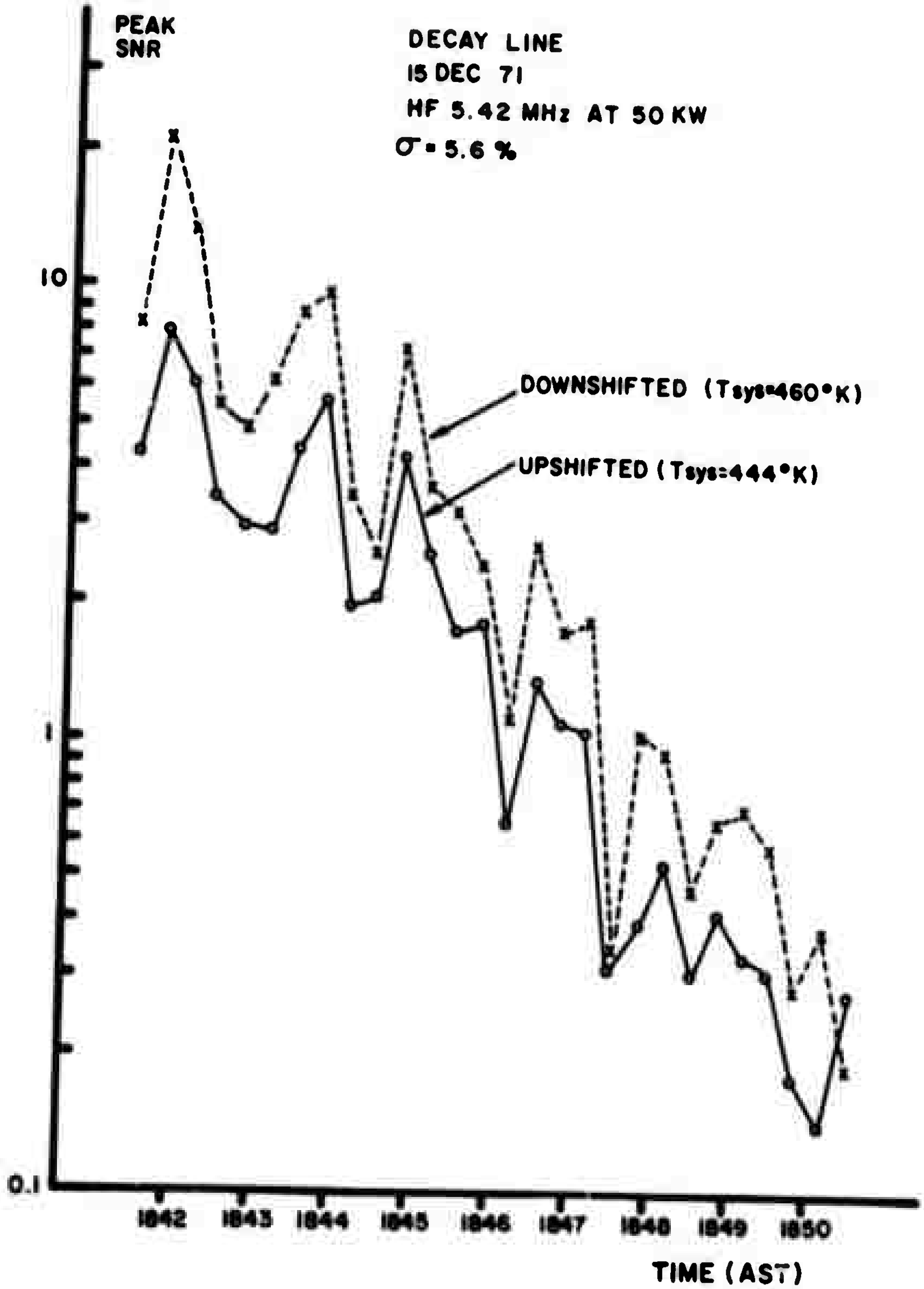

PEAK
SNR
DECAY LINE
15 DEC 71
HF 5.42 MHz AT 50 KW
σ = 5.6 %
10
1
0.1
DOWNSHIFTED (Tsys=460°K)
UPSHIFTED (Tsys=444°K)
1842
1843
1844
1845
1846
1847
1848
1849
1850
TIME (AST)

FIGURE 3

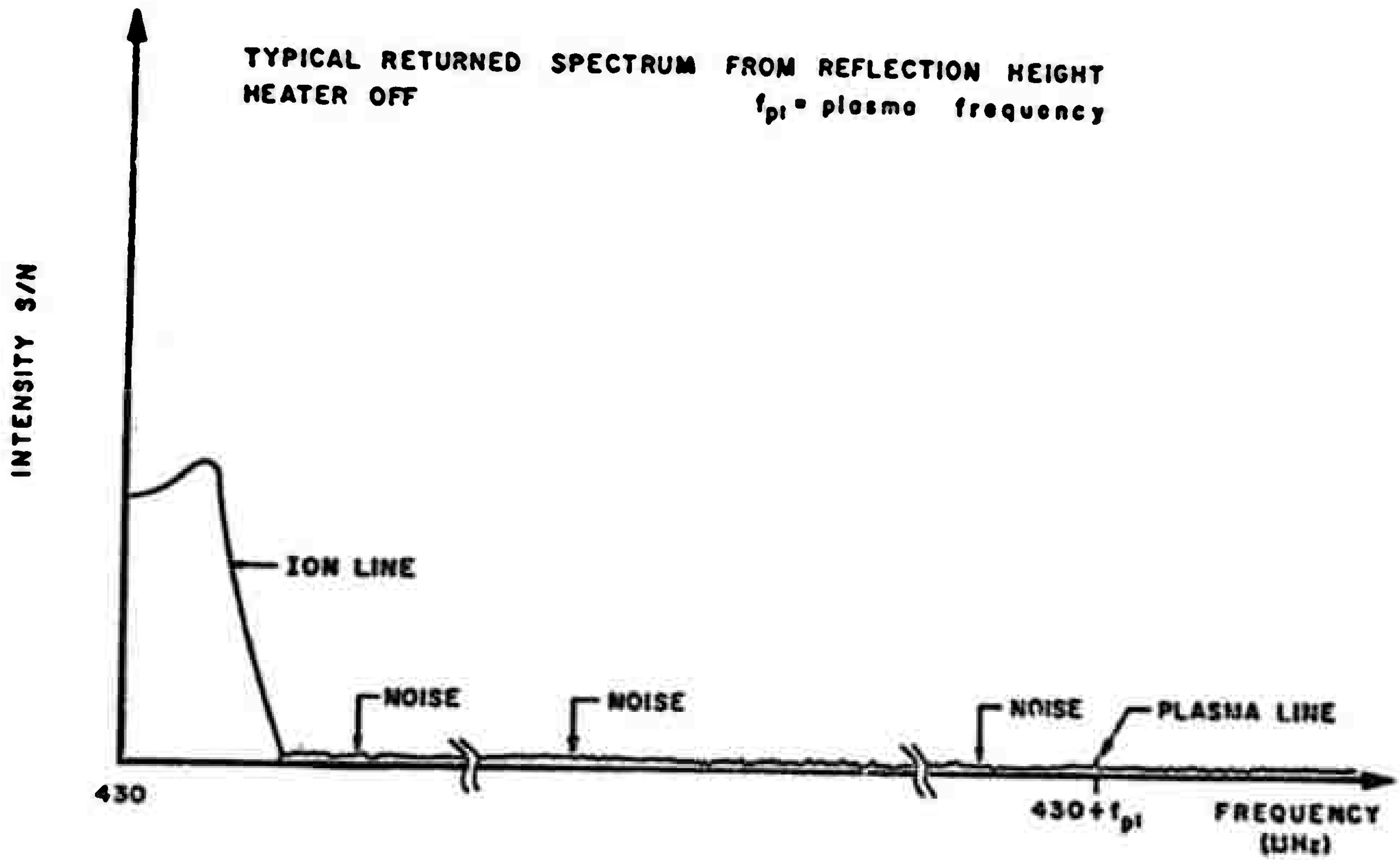

TYPICAL RETURNED SPECTRUM FROM REFLECTION HEIGHT
HEATER OFF
f_{pl} = plasma frequency
INTENSITY S/N
ION LINE
NOISE
NOISE
NOISE
PLASMA LINE
430
430 + f_{pl}
FREQUENCY (MHz)

FIGURE 4

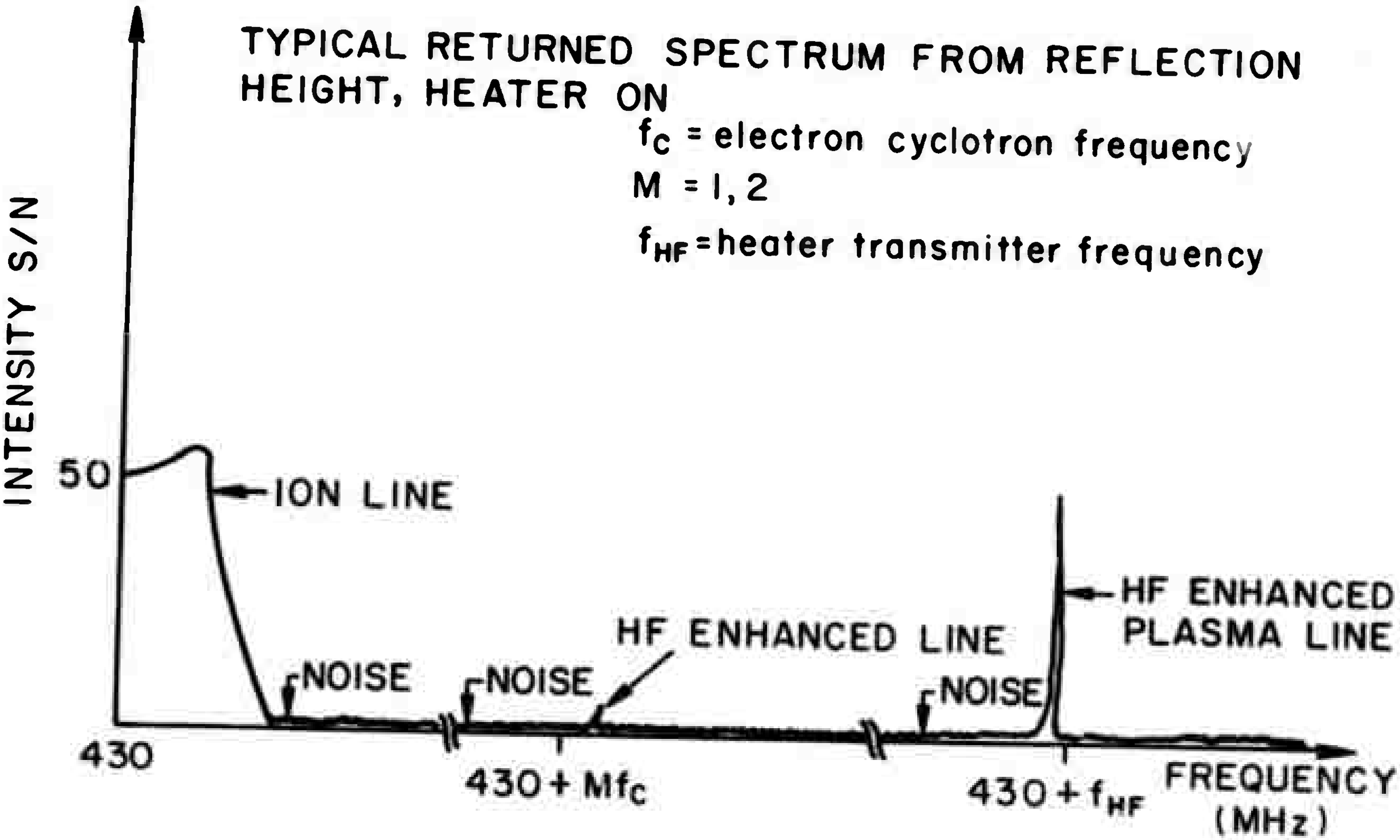

TYPICAL RETURNED SPECTRUM FROM REFLECTION HEIGHT, HEATER ON
f_C = electron cyclotron frequency
M = 1, 2
f_{HF} = heater transmitter frequency
INTENSITY S/N
50
ION LINE
NOISE
NOISE
HF ENHANCED LINE
NOISE
HF ENHANCED PLASMA LINE
430
430 + Mf_C
430 + f_{HF}
FREQUENCY (MHz)

FIGURE 5

Frequency Spectrum
Near Electron Cyclotron Frequency

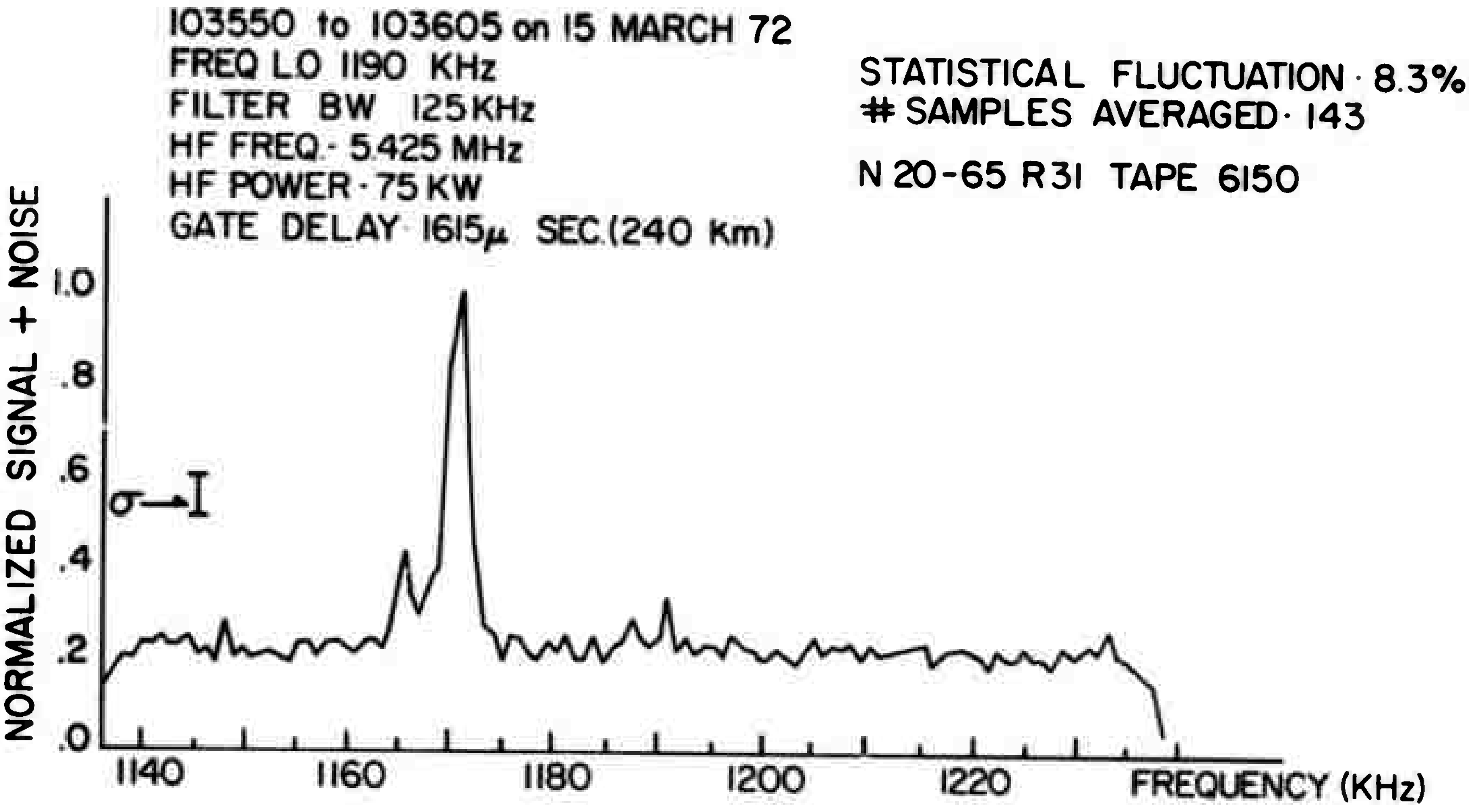
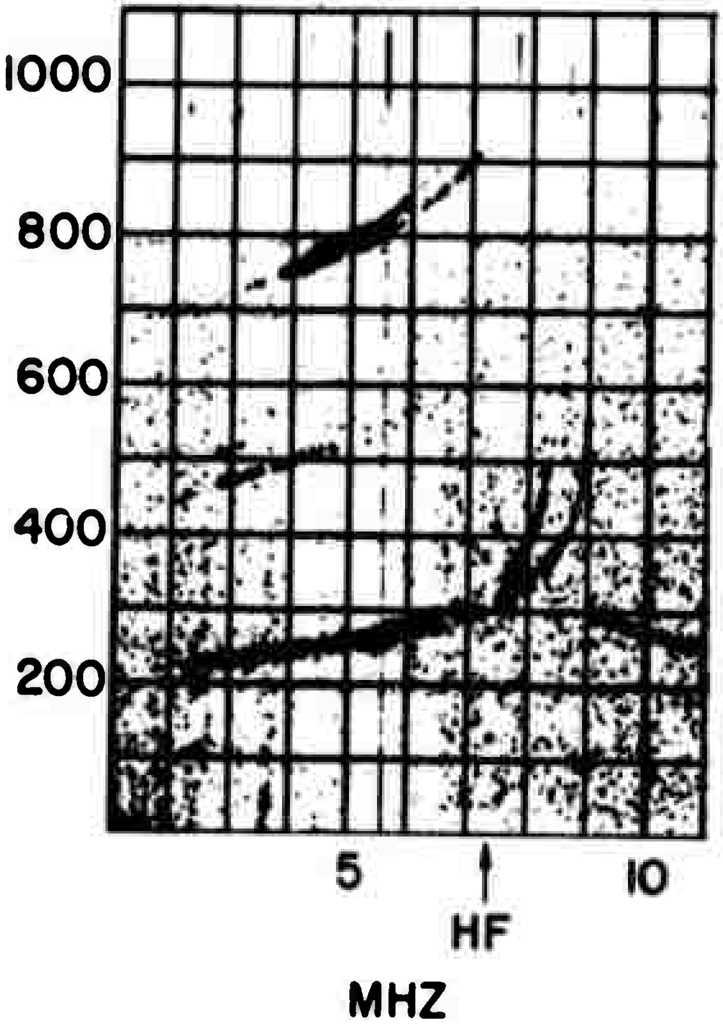


FIGURE 6

2015 AST



19/07/71

HF 7.31 MHZ
Power 55 KW
On 1958
Mode X

FIGURE 7